Practical challenges to estimating the benefits of agricultural R&D: The case of plant breeding research

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1. Introduction

Impacts assessment studies consistently show that the economic benefits generated by plant breeding research are large, positive, and widely distributed. Case studies too numerous to mention have concluded that investment in crop genetic improvement generates attractive rates of return compared to alternative investment opportunities (for reviews, see Echeverria 1990, Alston et al. 2000, Evenson 2001) and that welfare gains resulting from the adoption of modern varieties (MVs) reach both favored and marginal environments and are broadly shared by producers and consumers (for examples, see Lipton 1989, Hazell and Ramasamy 1991, Renkow 1993, Byerlee 1994). Swayed by the large body of empirical evidence that supports these findings, governments, lending agencies, philanthropic organizations, and private corporations have invested millions in plant breeding research.

But just how reliable are the results of studies that estimate the benefits of plant breeding research? Are the methods used to conduct such studies theoretically sound? And are the data sufficiently complete and accurate?

This paper reviews methods used to estimate the benefits of plant breeding research and discusses issues that often receive inadequate attention in applied impacts assessment work. Our goal is not to question the validity of the general theoretical frameworks commonly used to estimate the benefits of plant breeding research. Nor is it our intention to elaborate the many difficult conceptual issues that complicate research evaluation in general. Rather, our objective is to examine practical problems that may arise when the widely accepted theoretical frameworks are used for empirical analysis of plant breeding research and to propose workable solutions.

The problems that affect the empirical evaluation of plant breeding research tend to vary according to the objectives and scope of each study. Problems encountered during studies that focus on individual plant breeding programs are often quite different from problems encountered during studies that examine crop improvement networks made up of many plant breeding programs. Generally speaking, however, most can be grouped into three basic categories:

(1) problems associated with measuring adoption and diffusion of MVs, (2) problems associated with estimating benefits attributable to the adoption of MVs, and (3) problems associated with assigning credit among the various plant breeding programs that participated in developing the MVs. In the following three sections of the paper, we discuss each of these categories and present practical guidelines designed to help those engaged in plant breeding evaluation studies to avoid pitfalls that if ignored can lead to incorrect results. We conclude by discussing the effects that the problems may be having on applied impacts assessment work.

2. Measuring the adoption and diffusion of MVs

Plant breeding research generates economic benefits when MVs are taken up and grown by farmers. Depending on the circumstances, MVs can deliver different types of benefits, including higher yields, improved output quality, lower production costs, simplified crop management requirements, or shorter cropping cycles. (Measurement of these different types of benefits is discussed in Section 3.) Regardless of the type of benefits, however, the amount of benefits and their economic value depends on the size of the area planted to MVs. Therefore the first step in calculating the benefits of plant breeding research is to estimate the area planted to MVs.

In principle, estimating the area planted to MVs should be relatively easy. In practice, it is often very difficult. The practical difficulty relates partly to the difficulty of defining MVs and partly to the difficulty of measuring the area planted to MVs. These challenges are discussed in the following two sections.

2.1 Defining modern varieties (MVs)

Estimating the area planted to MVs is complicated by the fact that it is often not clear just what constitutes an MV. Conventionally, the term "modern variety" refers to improved varieties developed by scientific plant breeding programs.[1] If such varieties were readily identifiable in

1 In the past, the products of scientific plant breeding programs were commonly referred to as "improved varieties," reflecting the fact that their characteristics have systematically been altered in ways that bring economic benefits to those who grow them. Although use of the term improved is appropriate in this context, an unfortunate consequence of the convention is that landraces, the traditional varieties grown by farmers, often end

the field and unchanging through time, estimating the area planted to MVs would be relatively easy. Unfortunately, improved varieties produced by scientific plant breeding programs are not always readily identifiable in the field and unchanging through time, which is why definitional problems can arise.

MVs are not always readily identifiable in the field for the obvious reason that the economically valuable characteristics that are bred into MVs cannot always be detected simply by looking at a standing crop. In some cases, MVs have distinct physical characteristics that are easily visible and that distinguish them from other cultivars (e.g., plant height, leaf shape, flower color). In other cases, however, the characteristics that distinguish MVs from other cultivars may not be readily apparent, at least not to non-expert observers (e.g., resistance to pests or diseases, drought tolerance, heat or cold tolerance, improved storage quality, increased nutritional content).

Even when MVs can be identified visually, estimating the area planted to MVs may still be difficult, because MVs do not remain unchanging through time. Whenever farmers save harvested seed and replant it in a subsequent cropping cycle—a common practice in many developing countries—cultivars undergo genetic changes. These changes are especially pronounced in cross-pollinating species, although they also affect self-pollinating species. Morris, Risopoulos, and Beck (1999) identify possible sources of genetic change in maize crops grown from farm-saved or "recycled" seed. Some of these possible sources of genetic change are intentional (e.g., farmers' deliberate seed selection practices), while others are inadvertent (e.g., unintentional seed mixing, contamination by foreign pollen, genetic drift, random mutation, natural selection, segregation).

Regardless of whether genetic changes taking place in farmers' fields are intentional or inadvertent, and regardless of whether the consequences are welcome or unwanted, the result is the same: over time, the characteristics of successive generations of MV plants grown from recycled seed diverge from the characteristics of the original generation of MV plants grown

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up being considered unimproved. This is clearly incorrect. Landraces have been subjected to numerous cycles of improvement at the hands of farmers, many of whom are skilled at identifying superior germplasm and expert at selecting individual plants that embody desired traits.

from freshly purchased commercial seed. Eventually a point is reached at which the latest generation of plants differs from the original generation in one or more key characteristics. At that point, one must ask if the benefits attributable to the MV still exist, whether they have been partly eroded, or whether they have been completely lost.

2.2 Measuring the area planted to modern varieties (MVs)

Assuming the definitional problem can be resolved and there is agreement on what constitutes an MV, then it should be possible to estimate the area planted to MVs. Depending on the context, the estimation procedure may involve a static dimension (area planted to MVs at a given point in time) or a dynamic dimension (rate of diffusion of MVs through time). These are considered separately in the following two sub-sections.

2.2.1 MV adoption at a given point in time

Three types of data are commonly used to estimate the area planted to MVs at a given point in time: (1) farm-level survey data, (2) seed sales data, and (3) expert opinion.

Farm-level survey data: The most reliable way to estimate the area planted to MVs is using farm-level survey data. If such data are available, then MV adoption rates can be estimated with considerable accuracy. Unfortunately, farm-level survey data are rarely available, because surveys are expensive and time consuming to conduct. Even when farm-level data are available, the spatial and/or temporal coverage is often incomplete, because varietal adoption surveys are rarely carried out at the national level, especially on an annual basis. MV adoption statistics are published annually in many countries, but usually these statistics are generated by interpolating from data collected through surveys carried out at periodic intervals.

Seed sales data: In the absence of farm-level survey data, an alternative method for estimating the area planted to MVs involves the use of seed sales data. The area planted to MVs can be estimated as $A_{MV} = Q_s / r$, where A_{MV} is the area planted to MVs, Q_s is the quantity sold of commercial MV seed, and r is the average planting rate (expressed in terms of quantity of seed planted per unit land area, e.g., kilograms of seed per hectare).

Use of seed sales data to estimate the area planted to MVs is subject to at least four potential problems. First, data on commercial seed sales usually do not include farm-saved seed or seed produced outside the formal seed sector, so the method will give misleading results if a significant area is planted to farm-saved or “artisanal” seed. Therefore the method works best for crops grown mainly from commercial seed, which restricts its usefulness in many developing country contexts. Second, even when most seed planted is commercial seed, data on commercial seed sales must be treated with caution, because seed organizations may have incentives to misrepresent their production and sales figures. Third, the seed-based method will give incorrect results if there are significant discrepancies between the amount of seed that is produced, the amount of seed that is sold, the amount of seed that is planted, and the proportion of the planted area that is eventually harvested. Fourth, unless farmer surveys have been carried out, reliable information about average planting rates may not be available. While it is always possible to use recommended planting rates, farmers do not always follow recommendations.

Expert opinion: When neither farm-level survey data nor seed sales data are available, as a last resort the area planted to MVs usually can be estimated based on expert opinion. In most countries, it is possible to identify individuals who can “guesstimate” the area planted to MVs with a reasonable degree of accuracy. Typically such individuals include directors of agricultural research organizations, experienced plant breeders, practicing extension agents, and seed industry representatives. These people acquire knowledge of MV adoption patterns through their daily work experiences and have frequent opportunities to observe MV use in the field. While MV adoption estimates based on expert opinion can be quite accurate, one potential danger of relying on expert opinion is that certain individuals may have incentives to provide biased estimates. Therefore when the area planted to MVs is being estimated based on expert opinion, it is advisable to survey several experts and to base the final estimate on the consensus view, rather than relying on the estimate of a single person.

2.2.2 MV diffusion through time

For some types of impacts studies, it is desirable to estimate not only the area planted to MVs at a specific point in time, but also the rate of diffusion of MVs through time. Estimation of MV diffusion rates is particularly important when the objectives of the study include calculating financial measures of project worth, such as the net present value (NPV) and the internal rate of return (IRR). These measures depend on the temporal distribution of research costs and benefits, which in the case of plant breeding programs depends on the rate of diffusion of MVs.

MV diffusion rates can be expressed in two ways: (1) in terms of the percentage area planted to MVs, or (2) in terms of the percentage of farmers using MVs. The two measures frequently differ, because farmers who adopt MVs often plant less than 100% of their farm to MVs. For simplicity, here we will discuss diffusion in terms of the percentage area planted to MVs.

In the absence of evidence suggesting otherwise, most studies on the diffusion of MVs assume that the cumulative proportion of the area planted to MVs follows the S-shaped or "logistic" pattern first described by Everett Rogers in his classic study on the diffusion of innovations (Rogers 1962). The logistic diffusion curve assumes that there is slow initial growth in MV use, followed by more rapid uptake of MVs, followed in turn by a slowing down in additional MV use as the cumulative proportion of the area planted to MVs approaches its maximum or ceiling level. Mathematically, the logistic curve is described as $Y_t = K / (l + e^{-a-bt})$, where Y_t is the cumulative percentage of adoption at time t, K is the upper bound of adoption (adoption ceiling), *a* is a constant related to the time when adoption begins, and *b* is a constant related to the rate of adoption. Given sufficient observations on Y_t, it is possible to estimate the unknown parameters K, *a*, and *b* using non-linear regression methods. In cases where at least three observations on Y_t are available, and assuming that K can be estimated independently, a more practical approach is to use ordinary least-squares regression to estimate a transformed version of the logistic curve equation: $\ln [Y_t / (K - Y_t)] = a + bt$. The adoption ceiling (K) can be estimated using several different methods (CIMMYT Economics Program 1993). If diffusion is well advanced and adoption rates are known for several points in time, the simplest method is to plot the data and select a level that appears to be the upper bound. An alternative method is to run the regression using several different values for K and select the value that maximizes R^2 (this method simply ensures the best fit for the data; the t-statistics and R^2 from the regression have no meaning).

Use of logistic curves to estimate the diffusion of MVs is subject to several potential problems. As originally described, the logistic diffusion curve was based on a number of assumptions that included the presence of a large, non-homogeneous population of potential adopters who have unequal access to information about innovations and who differ in their willingness to innovate. When this assumption is violated, the probability increases that the diffusion path will diverge from the expected smooth S-shaped function. For this reason, while logistic curves are often appropriate for estimating MV diffusion over an extended period and across a large area, they are not always appropriate for estimating MV diffusion within a short period or in a restricted area.

Another potential problem with logistic diffusion curves is that they are based on the implicit assumption that technology adoption is non-reversible. For successful innovations, this is generally the case, especially at the aggregate level. However, it is not always the case. It is not uncommon for farmers to take up a new technology, experiment with it for some time, and then discontinue using it. With MVs, disadoption can occur for a number of reasons. Most obviously, the MV may turn out to be unprofitable. Examples abound in which MVs have been introduced into areas where they were not well adapted, with disappointing results. Alternatively, changes in external factors may over time erode the profitability of MVs. In Kenya, for example, the area planted to hybrid maize has dropped in recent years following steep increases in the price of fertilizer that have eroded the profitability of hybrid seed. Finally, a good MV may simply be eclipsed by a better MV. In fact this frequently happens: farmers often abandon older MVs and replace them with newer MVs. Given the possibility of disadoption, the classic upward-sloping logistic curve may not always be appropriate for estimating the diffusion of MVs.

3. Estimating the benefits associated with adoption of MVs

The second category of problems that commonly affect the empirical evaluation of plant breeding research involves the estimation of benefits associated with adoption of MVs. Measurement of different types of benefits is discussed in this section.

3.1 Estimating farm-level yield gains

The economic benefits that result from the adoption of MVs depend on the productivity gains that MVs deliver when they are grown by farmers. For simplicity, productivity gains are usually measured in terms of yield gains, expressed as additional units of grain harvested per unit land area. For various reasons, yield gains observed in varietal evaluation trials may not be equivalent to yield gains realized by farmers under actual production conditions. This must be taken into account if the benefits from plant breeding research are to be accurately measured.

No standard method exists for measuring yield gains. Varietal evaluation trials may be conducted on experiment stations, in farmers' fields under researcher management, or in farmers' fields under farmer management. Usually multiple replications are involved; these may be in the same location or in different locations. Either the maximum yield at a single location or mean yields across all locations may be reported. The various types of varietal evaluation trials all provide useful information, but it is unlikely that any single measure derived from trial results will exactly reflect how a variety will perform in large-scale plantings in farmers' fields. Yields of varieties grown in trials will almost always be higher than yields of the same varieties grown in farmers' fields under farmer management, so when yield gains associated with MV adoption are calculated based on trial data, the absolute value will often be overestimated.

Absolute yield gains observed in trials may differ from yield gains realized in farmers' fields for at least six reasons. First, trials conducted on experiment stations may not be planted under representative environmental conditions. Second, even when trials are conducted in farmers' fields under representative environmental conditions, they may be involve technology that most farmers do not regularly use. Third, when trials are conducted in farmers' fields using farmers' current management practices, this sometimes fails to take into account that MV adoption would induce changes in management practices as farmers choose economically optimal levels of inputs. Fourth, variability between farmers may be a problem. Even if all farmers act rationally and base input use decisions on economic considerations, use of inputs may vary from one farmer to the next because of supply-side constraints. For example, factors of production such as land and labor may be readily substitutable for some farmers and not for others (Alston, Norton, and Pardey 1995). Fifth, yield gains observed in varietal evaluation trials may differ from those realized in farmers' fields because farmers are inefficient in their use of resources. Resource use inefficiencies are thought to be greater in periods of rapid technological change, so MV adoption may in and of itself contribute to resource use inefficiencies (Byerlee 1991, Ali and Byerlee 1992, Pingali and Heisey 2001). Sixth, estimation of yield gains attributable to MV adoption can also be complicated by genotype-by-environment (G x E) interactions. The genetic potential of any cultivar interacts with environmental factors, so the yield of any given MV will tend to vary across locations and between cropping seasons (Byth 1981).

A large body of case study evidence suggests that *absolute* yield gains observed in varietal evaluation trials are often higher than those achieved in farmers' fields, but it is empirically uncertain whether *relative* yield gains (yield gains expressed in percentage terms) are also higher (Byerlee and Moya 1993). If yields realized in farmers' fields increase by the same proportion as in evaluation trials, the relative rate of gain would be the same, even though the absolute gain would be smaller in farmers' fields.

3.2 Accounting for changes in crop management practices

The improved germplasm embodied in MVs is not the only source of productivity gains observed in farmers' fields. Changes in crop management practices are another source. The distinction is important, because if no allowance is made for changes in crop management practices occurring at the same time as changes in MVs, the benefits attributed to MV adoption may be overestimated. The issue arises frequently, because adoption of MVs is often accompanied by changes in crop management practices. MVs are frequently promoted as part of an improved technology package, and when farmers adopt MVs, in many cases they also adopt complementary inputs such as fertilizer, herbicide, and pesticide. Farmers may also change the method or timing of cultural practices, including land preparation, planting, fertilization, and weed and/or pest control.

In estimating the benefits attributable to plant breeding research, it is therefore necessary to distinguish between the “germplasm effect” on productivity and the “crop management effect” (Figure 1). From a technical point of view, the task can be challenging. Improved germplasm and improved crop management practices usually interact, so the productivity gains observed when the two are adopted simultaneously often exceeds the sum of the productivity gains observed when each is adopted independently. The relative importance of the germplasm effect and the crop management effect varies depending on the context. In cases in which MV adoption occurs without any changes in management practices, the entire yield gain can legitimately be attributed to the germplasm effect. But in cases in which MV adoption is accompanied by changes in crop management practices, the germplasm effect may represent a relatively small proportion of the overall yield gain. For example, Bell et al. (1995) report that only 28% of the weather-adjusted yield gains observed in bread wheat MVs in the Yaqui Valley of Northwest Mexico between 1968 and 1990 can be attributed to genetic gains.

In the absence of empirical evidence relating directly to the example at hand, as a general rule of thumb it is usually reasonable to assume that improved germplasm and improved management practices each contribute about 50% to observed yield gains in cereal crops (Bell et al. 1995, Thirtle 1995, Fuglie et al. 1996).

3.3 Accounting for non-yield benefits

Our discussion of economic benefits thus far has focused on the value of additional crop production associated with adoption of MVs. Benefits that do not show up in the form of increased crop yields have not been considered. Examples include improved grain quality, improved fodder and straw quality, and reduced crop growth cycles. Non-yield benefits can be very important; sometimes they even exceed the value of yield benefits.

Quantifying and valuing non-yield benefits can be difficult, but it is usually not impossible. The appropriate methodological approach will vary depending on the nature of the benefit and the manner of its expression.

- *Improved grain quality:* Improvements in grain quality can be reflected in many different ways—improved milling and baking quality, improved storability, improved nutritional content, etc. In commercial agriculture, improvements in grain quality are often reflected in price differentials for marketed grain, making quantification and valuation of benefits is relatively straightforward. For example, Brennan and Davis (1996) used market price differentials as a basis for estimating the benefits generated by the Australian national wheat breeding program. In subsistence-oriented agriculture, on the other hand, improvements in grain quality are rarely reflected in market price differentials, making them much more difficult to quantify and value. Grain quality factors are often cited as having contributed to successful adoption of MVs (for example, see Smale 1995), but relatively few attempts have been made to quantify and value the economic benefits associated with improved grain quality in non-commercial farming systems.

- *Improved fodder or straw quality:* Improvements in fodder or straw quality may be reflected in easier processing, better storability, improved palatability, and improved nutritional value for animals. In commercial production systems improvements in fodder or straw quality are often reflected in terms of price differentials for marketed by-products, making quantification and valuation of benefits relatively straightforward. In subsistence-oriented agriculture, however, improvements in fodder or straw quality are rarely reflected in market price differentials, making them much more difficult to quantify and value.

- *Reduced growth cycle:* Reductions in the growth cycle of a crop can represent a significant benefit even in the absence of any increases in yield potential. Short-duration varieties are attractive to farmers because they can be harvested earlier than full-duration varieties, making them less susceptible to weather-related abiotic stresses occurring late in the growing season (e.g., drought, waterlogging, extreme heat or cold). Furthermore, since short-duration varieties can be planted later or harvested earlier than full-duration varieties, they often can be accommodated more easily into multi-crop rotations, thus affording farmers with opportunities to increase the productivity of their overall cropping system.

3.4 Increasing yield potential vs. maintaining current yields

Over time, most successful crop breeding programs generate genetic gains in yield. When yield gains are being achieved, starting at some time 0, each variety released at some subsequent time t yields more compared to a variety released at time 0 ($Y_t > Y_0$). Yield gains are realized incrementally with the periodic release of individual varieties, so gains in a series of varieties released over time will not follow a smooth trajectory. For most applied impacts studies, however, it can be assumed that over the long run yield gains follow a smooth pattern.

Genetic gains in yield have several different components. The most obvious component is increased yield potential. Theoretically, increases in yield potential are measured with potential stresses set at non-limiting levels, so they can be thought of as increases in maximum yields.

Another, less obvious component of yield gains is increased stress resistance. In addition to selecting for increased yield potential, many plant breeding programs select for improved host plant resistance to biotic and abiotic stresses. Conceptually, the distinction between increases in yield potential and increases in stress resistance is straightforward. Consider an important stress affecting a crop grown in a region targeted by a particular breeding program. Varieties released over time by the breeding program may yield more regardless of whether or not the stress is present. Alternatively, varieties released over time by the breeding program may yield more when the stress is absent and the same when the stress is present. Finally, varieties released over time by the breeding program may yield the same when the stress is absent and more when the stress is present. In the first instance, yield gains are attributable to gains in both yield potential and stress resistance. In the second instance, yield gains are attributable to gains in yield potential only. In the third case, yield gains are attributable to gains in stress resistance only.

Evans and Fischer (1999) and Tollenaar and Wu (1999) describe alternative approaches for distinguishing between increases in yield potential and increases in stress resistance. Most plant breeders appear to be quite comfortable with the distinction, at least conceptually. In practice, however, they may have difficulty distinguishing between the two sources of yield gains, since even the best-managed experiments usually are subject to stresses of one kind or another.

Yield gains attributable to increased stress resistance are particularly tricky to measure when stress resistance deteriorates over time. This often happens with disease resistance, because mutations in disease pathogens frequently arise to overcome genetically based resistance in the plant. Figure 2 depicts a case in which disease resistance breaks down over time. In cases such as this, it may be desirable to disaggregate total gains in disease resistance into gains resulting in improvement in resistance and gains resulting from maintaining resistance at the levels present in previously released varieties at the time of their release. Research aimed at avoiding losses from deteriorating stress resistance is called *maintenance research*.[2]

Casual inspection of the case study literature suggests that increased stress resistance is rarely recognized, leading to the suspicion that yield gains attributed to increases in yield potential often may be due to increases in stress resistance (Sayre et al. 1998). In cases in which increases in stress resistance are explicitly acknowledged, improvements in disease resistance and maintenance of disease resistance are usually not distinguished, much less measured separately.

In principle, measuring the benefits of stress resistance research is no different from measuring the benefits of productivity-enhancing research. In both cases, the basic idea is to compare the “with research” scenario to the “without research” scenario. However, the nature of the two scenarios differs. The difference is illustrated in Figure 3. In the case of productivity-enhancing research, the "without research" scenario is represented by the supply function S_0. The "with research" scenario is represented by a rightward (downward) shift in the commodity supply function to S_1. The area *abcd* under the demand curve (D) between S_1 and S_0 represents the economic surplus generated by the productivity enhancement research.

In the particular case of maintenance research, the supply function shifts in a different way. In the face of declining productivity (e.g., caused by declining disease resistance), under the

[2] Methods for quantifying and valuing the benefits of improved stress resistance are most commonly described in the literature on maintenance breeding (see Byerlee and Moya 1993; Brennan, Murray, and Ballantyne 1994; Morris, Dubin, and Pokhrel 1994; Byerlee and Traxler 1995; Collins 1995; Smale et al. 1998; Maredia and Byerlee 1999; Townsend and Thirtle 2001; Marasas, Smale, and Singh 2002).

"without research" scenario supply will not remain at S_0. Unless old, susceptible MVs are replaced by new, resistant MVs with similar productivity potential, the amount of output produced per unit of input will decline, resulting in a leftward (upward) shift in the supply curve to S_2. Maintenance research can be conceptualized as research needed to prevent leftward (upward) movement in the supply curve. The benefits from this research are the economic surplus generated by avoiding the leftward (upward) shift, represented in Figure 3 by the area *abcd* under the demand curve between S_0 and S_2. In practice, MV adoption and loss of disease resistance are gradual processes that occur simultaneously (Collins 1995). If a plant breeding program engages in both productivity-enhancing and maintenance research over an extended period, the total benefits would be the area *cdef* under the demand curve between S_2 and S_1.

Plant breeders have long argued the importance of maintenance research, but economic analyses of maintenance research are scarce (for a review, see Marasas, Smale, and Singh 2002). In principle, if supply with and without maintenance research is carefully estimated, projected total benefits should include the results of both productivity and maintenance research. In practice, ignoring maintenance research may lead to underestimation of benefits (Thirtle *et al*. 1998; Heim and Blakeslee 1986; Adusei and Norton 1990; Marasas, Smale, and Singh 2002). In some cases, analysts may wish to disaggregate total benefits into benefits attributable to productivity-enhancing research and benefits attributable to maintenance research. This requires estimation of two separate "without research" scenarios.

3.5 Estimating benefits from programs releasing streams of varieties

Successful plant breeding programs do not incur costs during a fixed period only to release a single variety (or a single set of varieties) as a one-off event. Successful breeding programs incur costs on an ongoing basis and release streams of varieties over time. Maredia and Byerlee (1999) present a stylized adoption model that accommodates sequential releases of multiple varieties over an extended period (illustrated in Figure 4). The model allows the benefits of crop improvement research to be divided into benefits derived from Stage I productivity gains (associated with initial adoption of MVs) and benefits derived from Stage II productivity gains (associated with the replacement of older MVs with newer MVs). Stage I gains are often dramatic, because they tend to occur within a brief period. Stage II gains are usually much less dramatic, but over the longer run they often provide most of the benefits from plant breeding research (Byerlee and Moya 1993; López-Pereira and Morris 1994; Byerlee and Traxler 1995; Heisey, Lantican and Dubin 2002). In assessing the impacts of breeding programs that have released streams of MVs through time, it is important not to confound Stage I and Stage II effects. If productivity gains associated with the latest-generation MVs are attributed to the entire area planted to MVs during the entire time that MV diffusion occurred, then the research benefits will be overestimated (Morris, Dubin, and Pokhrel 1994; Maredia and Byerlee 1999).

3.6 Imagining the without-project (counterfactual) scenario

Many plant breeding impacts studies implicitly assume that in the absence of the breeding program being evaluated, the performance of the varieties being grown by farmers would have remained unchanged. This assumption is unrealistic, as usually there are alternative sources of MVs. Thus the relevant comparison is not between current performance and the performance that was being achieved at the time the breeding program was established, but rather between current performance and the performance that farmers would currently be achieving had the breeding program being evaluated not been established. This concept is well-known in the project analysis literature, in which it is referred to as the "with and without project" comparison (Gittinger 1980). In the specific context of plant breeding research, it has been discussed by Evenson (2000), Marshall and Brennan (2001), Evenson and Gollin (2002), and Morris (2002).

Figure 5 illustrates this problem using an example in which the benefits of the plant breeding program are measured in terms of yield gains attributable to adoption of MVs. The horizontal dashed line represents the average yield achieved by farmers prior to the establishment of the breeding program being evaluated. The upper solid line represents average yields achieved by farmers as the result of growing a total of seven MVs produced by the breeding program; since MV replacement occurs at irregular intervals, the line is stepped. A common mistake in many impacts studies is to assume that the yield gain attributable to the breeding program is the difference between the farmers' original yield and their current yield, represented by the vertical distance (a + b). A more realistic estimate would take into account the fact that yield gains would likely have been realized even in the absence of the breeding program being evaluated, because farmers would have grown MVs obtained from other sources. This so-called counterfactual scenario is represented in Figure 5 by the lower solid line. The yield gains that would have been achieved under the counterfactual scenario are represented by the vertical distance (b). The yield gains attributable to the breeding program being evaluated thus should be estimated as something less than the difference between farmers' original yields and their current yields; a more realistic estimate might be the yield gain represented by the vertical distance (a). Although it is impossible to know with complete certainty what would have happened to farmers' yields had the breeding program being evaluated not existed, some sort of subjective judgment is needed to account for the yield gains that would have been achieved under the counterfactual scenario.

3.7 Translating farm-level yield gains into aggregate supply response

In many cost-benefit studies of plant breeding programs, benefits at time t (B_t) are calculated as $B_t = gY_tX_{1t}P_t$, where g is the percentage gain in yields attributable to the breeding program, Y_t is yield at time t, X_{1t} is land area affected by the breeding program, and P_t is output price. When X_{1t} is held constant, this simplified approach implicitly assumes a perfectly inelastic supply function, which would be true if there is no substitutability among factors of production and if the area planted to each crop does not vary as the result of research-induced changes in profitability (Morris, Dubin, and Pokhrel 1994). The approach does not allow for factor price effects that could potentially be attributable to plant breeding research—price effects that might temper aggregate supply response and eventually affect the size and distribution of research benefits.

This implicit assumption is not always justified, because research-induced changes in profitability sometimes clearly do lead to changes in factor prices that in turn affect aggregate supply response. For example, considerable evidence from South Asia shows that during the Green Revolution, adoption of rice and wheat MVs often led to increased demand for labor (Ruttan 1977, Lipton and Longhurst 1985, Jayasuriya and Shand 1986). The increased demand for labor was linked to increases in harvesting and threshing operations associated with higher yields, as well as increases in cropping intensity facilitated by shorter duration varieties (Barker and Cordova 1978). So long as labor supply was less than perfectly elastic, increased demand for labor exerted upward pressure on wage rates in local labor markets, tempering aggregate supply response and furthermore affecting the welfare of households in adopting areas for whom agricultural labor was a source of household income.

The impact of new labor-using technology may additionally extend outside of the area in which the technology is adopted if laborers in non-adopting areas are mobile and if migration of laborers from non-adopting areas occurs. In addition to transferring some of the benefits of the new technology to migrating individuals, labor migration will also put upward pressure on wage rates in non-adopting areas (Quizon and Binswanger 1986, David and Otsuka 1994, Renkow 2000). Most studies that focus specifically on plant breeding research do not take into account the impacts in related markets, but if a major portion of the analysis concerns large-scale Green Revolution-type change, significant welfare impacts in labor markets may be overlooked.

While it is true that the size and distribution of research benefits can potentially be mismeasured if the responsiveness of aggregate supply to research-induced changes in factor prices is ignored, use of simplifying assumptions is sometimes justified. In the specific case of international wheat breeding, for example, Heisey, Lantican and Dubin (2002) show that over a plausible range of parameters for factor substitution and price responsiveness, use of simplifying assumptions does not lead to systematic over- or underestimation of research benefits. But whatever simplifying assumptions are made, they should be consistent with observed aggregate supply response for the crop in question (in the case of *ex post* analysis) or with plausible future aggregate supply response (in the case of *ex ante* analysis).

3.8 Dealing with price effects in output markets

Depending on the size and degree of openness of the economy in which a plant breeding program operates, research that leads to yield gains and supply increases may cause changes in output prices, which also could affect the size and distribution of benefits. If the country or region targeted by the breeding program is neither a net exporter nor a net importer of the crop, a research-induced outward shift in the aggregate supply curve will drive down the domestic price of the crop. For countries or regions that are net exporters, an outward shift in the aggregate supply curve will leave the domestic price of the crop unchanged at the export parity level, and for countries or regions that are net importers, an outward shift in the aggregate supply curve will leave the domestic price of the crop unchanged at the import parity level.

An extensive body of theoretical literature discusses the distributional impacts of technological change transmitted through price effects in commodity markets (Ayer and Schuh 1972, Akino and Hayami 1975, Renkow 1994). Over the long run, increases in global crop supplies resulting from international plant breeding research are likely to depress real world prices. Recent empirical work suggests that not only the size but also the distribution of research benefits will be affected by the assumptions made about the price responsiveness of supply and demand (Falck-Zepeda, Traxler, and Nelson 2002). The relative importance of the two effects—change in size of benefits vs. change in distribution of benefits—remains subject to debate, however. According to Alston, Norton, and Pardey (1995), while changes in real world prices of major commodities will slightly affect the total size of research benefits, the more important effect will be on their distribution between farmers and consumers.

3.9 Accounting for policy distortions

Estimating the benefits generated by plant breeding programs can be complicated in the presence of price controls, production quotas, trading regulations, exchange rate controls, and similar policies. By altering the financial profitability of agriculture, such policies can distort the incentives to adopt MVs and consequently increase or decrease the economic benefits attributable to MV adoption. For this reason, the benefits generated by a given plant breeding program depend only partly on the performance of the breeding program; they depend also on policy factors that in the end have little to do with research.

Can and should anything be done about this problem? In most cases, probably not. If the policy distortions are expected to remain in place, then to the extent that the benefits associated with MV adoption have been affected, the effect will be real. If on the other hand there is an expectation that the policy distortions will be removed, then in rare cases it may be feasible and worthwhile to project the likely impacts of their removal on MV adoption rates and to adjust the calculation of benefits accordingly.

4. Assigning credit for plant breeding research

The third category of problems that commonly affect the empirical evaluation of plant breeding research involves the attribution of credit among different breeding programs. Attribution problems are discussed in this section.

4.1 Dealing with research spillovers

Improved germplasm moves easily throughout the global plant breeding system. Virtually all professional plant breeders use germplasm that has been improved by others, not only breeding materials developed by other professional breeders, but sometimes also landraces selected by farmers. Conversely, whenever a plant breeder develops germplasm for one target environment, the same germplasm is often used in other target environments (Maredia and Byerlee 1999, Evenson *et al*. 1979). The existence of these “research spillovers” increases the overall benefits generated by the global plant breeding system, but at the same time it also complicates the task of assigning credit among individual breeding programs.

In some instances, it may be desirable to assess the contribution made by a particular breeding program that operates as part of a larger network of breeding programs. Two analytical approaches are possible. The first approach is to frame the problem as a variant of the "with research, without research" problem. Actual benefits and costs must then be compared with estimated benefits and costs that presumably would have prevailed in the absence of the breeding program being evaluated. The second approach is to calculate the benefits attributable to the entire network and then somehow apportion those benefits to the individual breeding programs that make up the network. Pardey *et al*. (1996) outline several apportionment rules that can be used for crops whose pedigrees are known. At one extreme, the "any ancestor" rule allows a breeding program to claim credit for all MVs having an ancestor from the breeding program. The “any ancestor” rule is useful for assessing the reach of a given breeding program, but it tends to overstate the influence of that program if used as a rule for benefit attribution. At the other extreme, the "last cross" rule attributes all the benefits from a given MV to the breeding program that made the final cross to produce the MV. The “last cross” rule tends to understate the benefits generated by breeding programs that develop source materials (as opposed to finished cultivars), and it tends to overstate the benefits generated by breeding programs that make a lot of crosses using source materials obtained elsewhere. In between the two extremes, the "geometric rule" apportions benefits over several generations of crosses, with later crosses getting more weight than earlier ones. The apportionment rules proposed by Pardey *et al*. are not always practical, especially when pedigree breeding systems are not being used, or when breeding information is proprietary. But in cases in which at least partial information is available about the genetic background of individual MVs, it may be possible to use rules such as the "any ancestor" rule or the "last cross" rule, since these do not require complete knowledge of the breeding history.

4.2 Disentangling complementarities between research and other factors

Crop genetic improvement research, like any other kind of research, does not take place in a vacuum. The impacts of plant breeding programs depend in part on external factors having little to do with plant breeding, for example, the seed supply system, the extension service, the crop marketing system, transportation and communications infrastructure, or even the school system through which farmers receive their basic education. Disentangling complementarities between plant breeding research and external factors such as these that affect the adoption and diffusion of MVs is a complicated task, and one that is usually far beyond the scope of a typical impacts assessment study. No attempt will be made here to describe methods for doing so.

5. Discussion

In recent years, research administrators, science policy makers, and finance agency officials have come under increasing pressure to justify public investment in agricultural research. As competing demands for government funds proliferate, better and more rigorous evidence is needed to show that agricultural research generates attractive rates of return compared to alternative investment opportunities. The result has been an upsurge in studies designed to assess the impacts of agricultural research, as well as an increase in the amount of research being undertaken to improve the methods used for carrying out applied impacts assessment work.

Few sub-fields within agricultural research have been subjected to as much scrutiny as plant breeding. Interest in the economics of plant breeding emerged after the dramatic and widely publicized impacts of the Green Revolution showed that relatively modest investments in crop genetic improvement could generate enormous benefits at the global level. Supporters of agricultural research seized on the success of the Green Revolution and commissioned a series of studies which predictably concluded that investment in international plant breeding had generated eye-popping returns. The results of the early impacts studies were later corroborated by numerous follow-up studies, many of which concluded that the benefits of plant breeding research have been not only large, but also broadly distributed. On the basis of a large body of empirical evidence, the economic attractiveness of plant breeding came to be widely accepted.

But just how reliable are the results of the many studies that estimate the benefits of plant breeding research? Are the methods used to conduct such studies theoretically sound? And are the data sufficiently complete and accurate?

Questions such as these will seem heretical to some. Within the community of impacts assessment practitioners, there is a general consensus that empirical evaluation of plant breeding programs is by now a routine undertaking. Certainly it is much easier to document the impacts of plant breeding research than it is to document the impacts of many other types of agricultural research. After all, the products of plant breeding research—MVs—are tangible things that can be observed in the field and whose characteristics can be objectively described and measured. This is not the case with many other types of research. The products of crop management research, for example, are farmer recommendations. Documenting the impacts of crop management research can be complicated, because the products cannot be observed directly. As a result, the impacts of crop management research often must be estimated indirectly by observing changes in farmers' behavior and somehow establishing a causal link to the research that gave rise to the recommendations (Traxler and Byerlee 1992).

This paper has described a number of practical problems that can complicate efforts to asses the impacts of plant breeding research. We have argued that despite the widely held belief that empirical evaluation of plant breeding programs is now a routine undertaking, documenting and measuring the impacts of crop genetic improvement research is subject to many potential problems. Failure to recognize and deal effectively with these problems can lead to incorrect empirical results, possibly leading to inappropriate policy analysis and non-optimal research funding decisions.

The problems that affect the empirical evaluation of plant breeding research will tend to vary according to the objectives and scope of each individual study. Generally speaking, however, they can be grouped into three basic categories: (1) problems associated with measuring adoption and diffusion of MVs, (2) problems associated with estimating benefits attributable to the adoption of MVs, and (3) problems associated with assigning credit among the different plant breeding programs that contributed to the development of the MVs. As we have shown, the problems vary widely in nature, ranging from the conceptual (*What is an MV?*) to the practical (*How can the area planted to MVs be measured?*) to the speculative (*What yields would farmers have achieved in the absence of the breeding program?*). The incidence of the problems varies widely as well. Some are very common, while others arise only rarely. And as we have discussed, correcting for these problems is easy in some cases, difficult in others. But regardless of their nature, incidence, or complexity, it is important that all of the problems be understood, because any one of them, if not recognized and resolved, can greatly influence empirical results. Many quantitative measures of project worth used to evaluate the performance of plant breeding programs—including the benefit/cost ratio (B/C), the net present worth (NPV), and the internal rate of return (IRR)—are very sensitive to changes in individual cost and benefit parameters, so even if only one parameter is incorrectly estimated, the consequences can be significant.

To what extent has failure to recognize and resolve the problems described in this paper influenced applied impacts assessment studies of plant breeding programs? To answer this question, it would be necessary to revisit a large number of case studies and systematically review their evaluation methods, something that is beyond the scope of this paper. However, our familiarity with the plant breeding evaluation literature leads us to suspect that it is far more common for research costs to be understated and/or research benefits to be overstated, rather than the inverse, leading to systematic inflation in performance measures. One recurring source of problems is the tendency of many analysts to ignore research spillovers, leading them to attribute to a single breeding program benefits that actually were generated by several breeding programs acting in collaboration. Based on our admittedly subjective impressions, we believe that the returns to investment in plant breeding research are probably not as high as is generally believed, certainly not in the triple-digit range as reported by some authors.

Does this mean that investment in plant breeding is economically unattractive? Certainly not. Even correcting for the methodological errors that appear to have affected many case studies, it seems clear that investment in plant breeding often generates significant payoffs. And while the returns to investment in plant breeding may have declined in recent years with increases in research costs, the returns are still attractive relative to most alternative investment opportunities.

Should applied researchers take more care in estimating the benefits of plant breeding research? We believe in many cases they should. While we are not advocating that elaborate measures should always be invoked to address every problem that could conceivably arise, we believe that the list of potential problems discussed in this paper can serve as a checklist for those seeking to estimate the benefits of plant breeding research. Although impacts studies are undertaken for many different reasons, in the long run the credibility of all impacts studies will depend to some extent on the attention paid to methodology in each individual evaluation exercise.

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Figure 1. Yield gain components: Germplasm vs. crop management effect

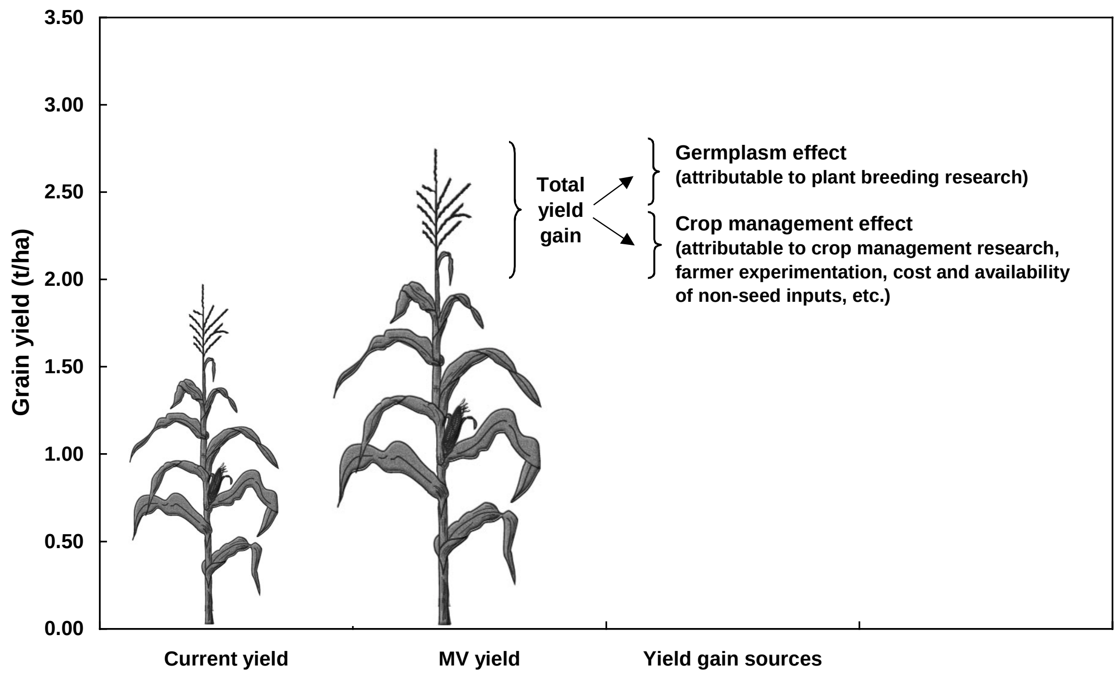
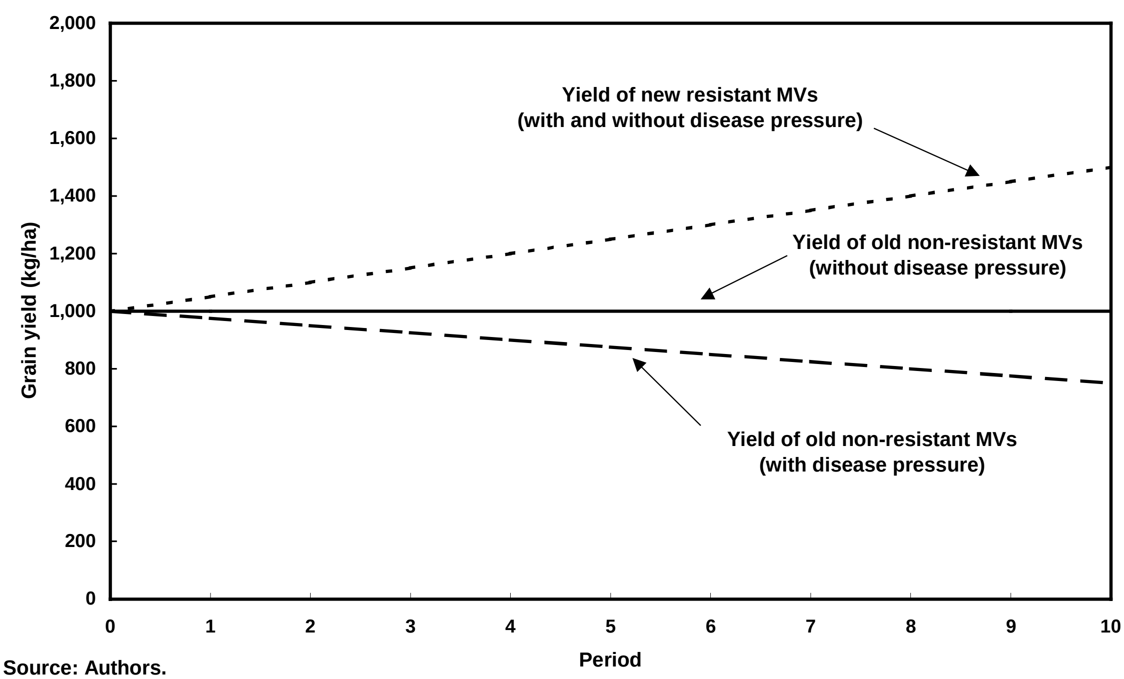
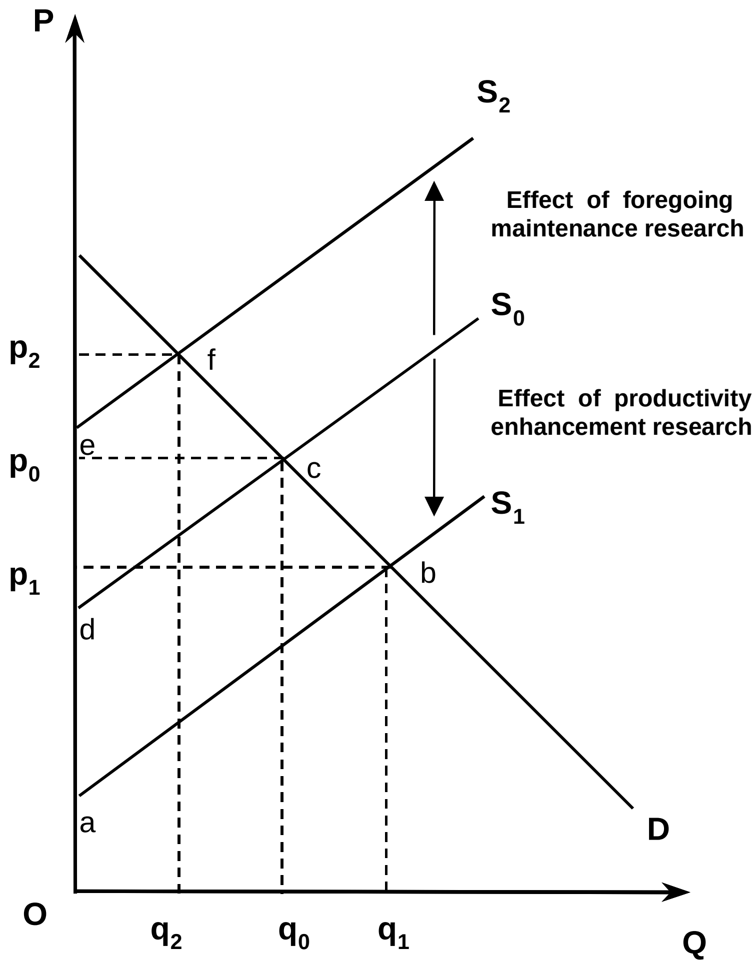


Figure 2. Yield gains given perfect disease resistance in new MVs



Source: Authors.



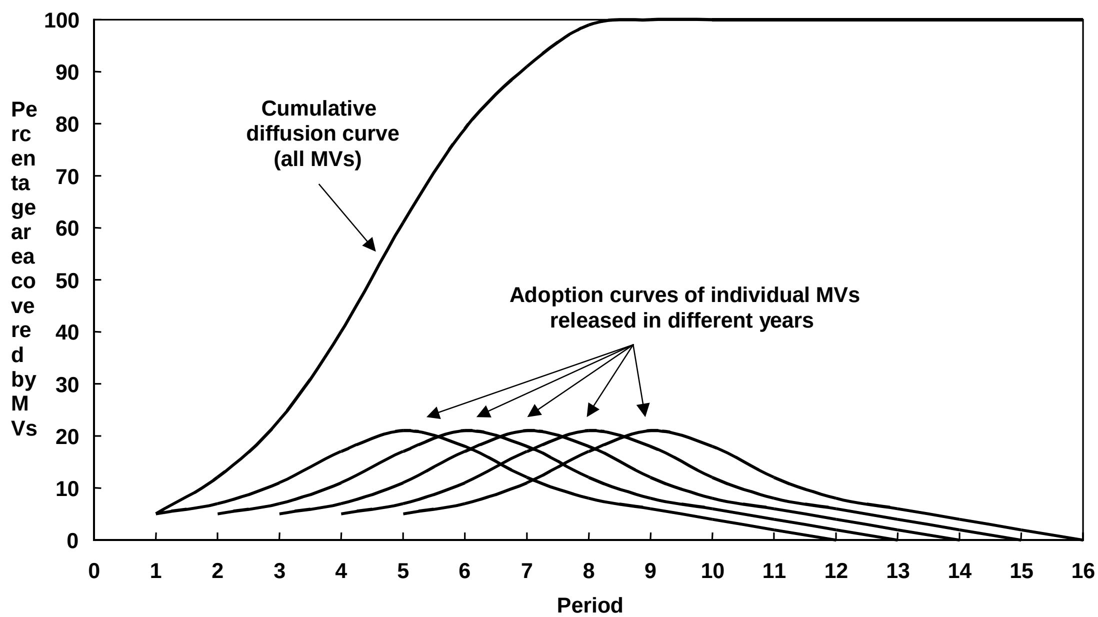
S_0 Supply with maintenance research, no productivity enhancement research
S_1 Supply with productivity enhancement research, full adoption of MVs
S_2 Supply with productivity losses from no maintenance or enhancement research

abcd = Surplus generated by maintenance research
cdef = Surplus generated by productivity enhancement research

Figure 3. Evaluating impacts of maintenance research (economic surplus model)

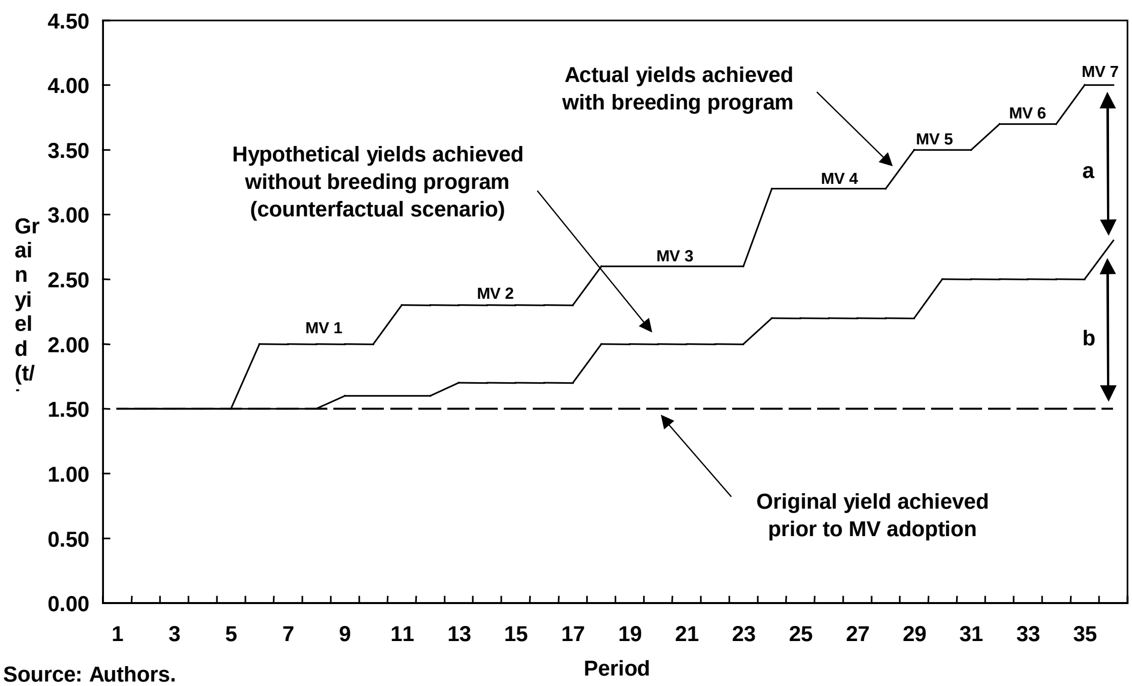
Source: Adapted from Marassas, Smale, and Singh 2002.

Figure 4. Cumulative diffusion of MVs released by a plant breeding program



Source: Maredia and Byerlee 1999

Figure 5. Estimating MV yield gains: Projecting the counterfactual scenario



Source: Authors.